Attenuation Distance of Low Frequency Waves Upstream of the Pre-Dawn Bow Shock: GEOTAIL and ISEE3 Comparison

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Received _____; accepted _____

to be submitted to the *Geophysical Research Letters*, 1994,

Short title: BOW SHOCK UPSTREAM WAVES

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Abstract. We have made a statistical study of the spatial distribution of low frequency waves (-0.01-0.1 Hz) in the region upstream of the pre-dawn to dawn side bow shock (-50 Re < X < 15 Re) using both GEOTAIL and ISEE-3 magnetometer data. We have found that the wave amplitude dependence on D and X_s, where D is the distance from the bow shock and X_s the x-coordinate position of shock foot point of the IMF, can be described by a functional form of $A \exp(X_s/L_X - D/L_D)$, with the characteristic attenuation distances, $L_X \sim L_D \sim 50$ Re.

Introduction.

The low frequency (< proton Larmor frequency) shock upstream waves have been studied extensively in the context of the wide-spread dissipation process at the quasi-parallel shock [*Fairfield*, 1969; *Hoppe et al.*, 1981; *Le and Russell*, 1992 and references therein], At the shock front, suprathermal ions (> several keV) are injected upstream by the specular reflection process [Paschmann et al., 1980] and/or the process intrinsically related to the shock formation process itself [H%& *et* al., 1990; *Scholer and Burgess*, 1992], These ions then excite low frequency magnetic waves through the ion-ion beam cyclotron instability [*Barnes*, 1970; *Watanabe and Terasawa*, *1981; Winske and Leroy*, 1985]. Extensive studies of these wave and ion properties, however, have been made mainly for the upstream region of X >-10 Re, and the study of upstream region of $X < -10$ Re is quite limited. In this letter, we present the result of st at istical study of wave amplitude distribut ion in the wide region of -50< X < 1 5 Rc, utilizing the magnetic field data from both ISEE-3 and GEOTAIL spacecraft,

Observat ions.

Figure 1 shows the orbits of these two spacecraft projected onto t he GSE (geocentric solar ecliptic) XY and X2 planes. A dashed curve in Fig. 1 shows the nominal shock location [*Fairfield*, 1971], (Average solar wind aberration is assumed to be 40,) The ISEE-3 spacecraft traveled the upstream region of the pre-dawn bow shock during the period of 24-30 September, 1983. *Terasawa et al.* [1985] discussed the properties of energetic ions (>30 keV) observed during this upstream interval, and concluded that the acceleration of these ions mainly occurs in the near-earth upstream region, and that the particle acceleration at the distant bow shock is weak. In this paper, we study the

upstream wave activities observed with ISEE-3 magnetic field experiment [*Frandsen et al.*, 1978]. A decade after (5 -9 August, 1993), the GEOTAIL spacecraft went through the upstream region of the pre-dawn bow shock on an orbit similar to ISEE-3's but closer to the nominal shock surface. The magnetometer experiment [*Kokubun et* al., 1994] also showed tho existence of large amplitude low frequency wave activity during this upstream period.

Figure 2 and 3 show the 5 min averages of 3 sec magnetic field data from ISEE-3 and GEOTAIL, respectively, Panels show from the top the total magnetic field intermit y $\bar{B}$, the longitudinal angle $\bar{\theta}$, and the azimuthal angle $\bar{\phi}$ (in the GSE coordinates). The bottom panels show the normalized fluctuation amplitudes $\delta B_\perp/|\bar{B}|$, where $\delta B_\perp$ is the ,5-rein standard deviation of the magnetic field fluctuation in the direction perpendicular to the average magnetic field direction, To avoid the effect of solar wind discontinuities or bow shock crossings on $\delta B_\perp$, we have made the following selection: First, we compare $\bar{B}, \bar{\theta}$, and $\bar{\phi}$ for successive 5-min intervals, of which the start times are shifted by 1 min. If either $\bar{B}, \bar{\theta}$, or $\bar{\phi}$ changed more than 1 nT, 2", or 4°, we exclude these intervals from the plots of $\delta B_\perp/|\bar{B}|$, as well as from the following statistical analysis. At the top of Fig. 2 and 3, shaded bars indicate when the spacecraft were upstream *of* the bow shock. Since GEOTAIL cruised close to the nominal bow shock location, it crossed more frequent ly the shock front than ISEE-3 did. The ISEE-3 obser vat ion during the period of 2526 September 1983 is not included, since this interval was affected by the passage of a corotating solar wind stream [*Terasawa et al.* 1985].

The magnetic fluctuation shown in the bottom panels of Fig. 2 and 3, were kept at high level (~0. 1-0.8) throughout the upst ream observation intervals except some intermittent disappearances. ¿From the inspection of the high time resolution magnetic field data (6 Hz and 16 Hz sampling for ISEE-3 and GEOTAIL), we have confirmed that these large amplitude fluctuation indicated the existence of the upstream waves *of* ~0.01-0.1 Hz. Figure 4 shows a typical example of the prover spectrum of the

perpendicular component observed during the interval of 1 :x9-1 :48UT on 6 August, 1993. A broad peak around 0.05 Hz with a high frequency tail is similar to what is usually observed in the near-earth upstream region several Re behind the ion foreshock boundary [*Le and Russell*, 1992], Since *Terasawa et al.*[1985] showed that the intensity of upstream ions (> 30 keV) in the pre-dawn upstream region is maximized when the IMF is in tho nominal Parker's spiral direction ($\theta \sim 0°$ and $\phi \sim 135°$ or 3150), we have checked how wave intensity depends on the IMF direction arid found dependence similar to that found for the ion intensity. 'To make a statistical study, we have selected 163 (05) mm-overlapping 5-rein intervals from ISEE-3 (GEOTAIL) observations, during which the IMF had $\tilde{\theta} = 0° \pm 15°$ and $\tilde{\phi} = 135 \pm 30°$ or $315 \pm 30°$, The normalized fluctuation amplitudes $\delta B_\perp / |\vec{B}|$ for these selected intervals are shown in Figure 5a and 5b, where the abscissa represents the coordinate X_s, which is the X_{GSE} coordinate of the shock foot point of a nominal IMF line (i.e. a field line with θ=0° and ϕ=135° or 315°) paining through each of these spacecraft. The GEOTAIL observation on Aug. 5 1999 is not included in Fig. 5b, since the spacecraft position was >5 Re behind the nominal shock position (Fig. 1).

We observe in Fig. 5a and 5b that the wave amplitudes show dependence on X_s increasing toward the shock subsolar point (at $X_s \sim 14$ Re), Fig. 5c shows the distance D along the IMF line from the nominal shock surface to the spacecraft, which we expect to be another controlling factor of the wave intensity. Since GEOTAIL was close to the bow shock, the dataset seems to have included large amplitude waves within the shock ramp region. In Fig. 5b, the nominal upstream intervals (open circles for 45 intervals) are discriminated from the near-shock intervals (dots for 20 intervals), within 30 min of which GEOTAIL crossed the bow shock. Solid curves in Figure 5a and 5b are the results of the least-square fitting of the functioned form of $A \exp(X_s/L_X - D/L_D)$ to the combined data sets of ISEE 3/G EOTAIL observations, where the near-shock intervals for G EOTAIL were omitted, The attenuation distances are Lx = 545- 9Re

and $L_D = 51 \pm 32 R_E$ with A = 0.404-0,04, Accounting the difference in numbers of 5 ruin intervals, we have set the statistical weights of ISEE-3 and GEOTAIL with a ratio of 1:4. The above statistical result shows $L_X \sim L_D$. Including the GEOTAIL near-shock data, we obtain $L_X = 554.10 R_E$ and $L_D = 36 \pm 15 R_E$ with $A = 0.43 \pm 0.04$ (dashed curves in Fig. 5*a* and 5b). In this calculation L_D is significantly smaller than Lx, However, L_D seems to be underestimated here owing to the contamination of data within the shock-ramp region,

Discussion.

We have compared the upstream wave observations from ISEE-3 and GIN-WAIL, whose acquisition times were separated over a decade. For such a comparison to be possible, we should have a similar solar wind condition, The basic solar wind parameters are tabulated in Table 1a and lb [*Rame et al.*, 1978; *Frank et al.*, 1994]. As seen in the tables, the solar wind conditions were not completely identical: The Alfvén Mach numbers M_A in the GEOTAIL period were generally larger than those in the ISEE-3 period. (Note that this difference in M_A is mainly caused by the higher number densities in the latter period than the former. The ranges of the solar wind velocity themselves overlapped, and were within the nominal variation width.) Under the high M_A condition the bow shock surface is expected to shrink behind the nominal position, so that the actual field-aligned distance D for GEOTAIL would be larger than that shown in Fig. 5c. The underestimation of D for GEOTAIL might have led us to overestimate the attenuation distance L_D. However, the fact that we observed bow shock crossings on Aug. 7 indicates that the effect of high M_A on the shock position was not substantial. For complete discussion, we should use the fast magnetosonic Mach number M_F instead Of M_A. Unfortunately, M_F for the ISEE-3 period is not available, since the ion temperature was not known. For the further refinement of the estimation of L_D and L_X, we are awaiting the compilation of the dataset from the another GEOTAIL orbit in the

period of June-July 1994 when the spacecraft prosed through the region more upstream than those in Figure 1.

We have found that the characteristic attenuation distances along the IMF, L_D, and along the shock surface, Lx, are ~ 50 Re. These attenuation distances are much longer than that obtained in the near-earth upstream region (~ 15 Re, *Fairfield,* [1969]) and that for the discrete wave packets (~2- 3 Re, *Le and Russell,* [1992]). The difference in attenuation distances may reflect different physical processes working in the different parts of the upstream region: The shortest distance from Le and Russell suggests that the whistler wave packet probably disperse very rapidly, Fairfield's number seems to simply represent the distance for which tho ions can travel before their isotropizaion by the self-excited waves (see, e.g. Mitchell et al. [1983]). The waves discussed in this paper have had more time to evolve spatially and temporally than waves treated in two earlier papers. Since the particle observation (ions of >30 keV) suggests that there is not a lot of additional free energy in the pre dawn upstream region [*Terasawa et al., 1985],* the large scale size there would imply that the waves are not rapidly damped, However, to study the variation of the mailable free energy, we should wait for the observational study of several -30 keV ions in this region, which wc shall plan to start in near future.

Acknowledgments. We are grateful 60 all GEOTAIL and ISEE-3 science members for their collaboration. portions of this work were done at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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This manuscript was prepared with the AGU LaTeX macros v3.0.

Figure 1. ISEE-3 and GEOTAIL orbits during the periods on the GSE-XY plane, between 23 September and 1 October, 1983, and between 4 and 10 August, 1993, respectively. The X% projection (panel a, top) and the XY projection (panel b, bottom) are shown. Stars show the positions at 00 UT of each day. A dashed curve in panel b shows the nominal bow shock surface.

Figure 2. ISED-3 observation of the magnetic field. The intensity B, the latitudinal angle θ, the azimuthal angle ϕ, the normalized fluctuation amplitude (see text) are shown from the top.

Figure 3. GEOTAIL observation of the magnetic field with the same format as Fig. 2.

Figure 4. The power spectrum of the magnetic field fluctuation perpendicular to the averaged field direction. ('The spectrum is calculated from 1800 point Fourier transformation with 5 degrees of freedom,) Observation was made between 1:39 and 1:48 UT on 6 August, 1993. The dot line is proton cyclotron frequency.

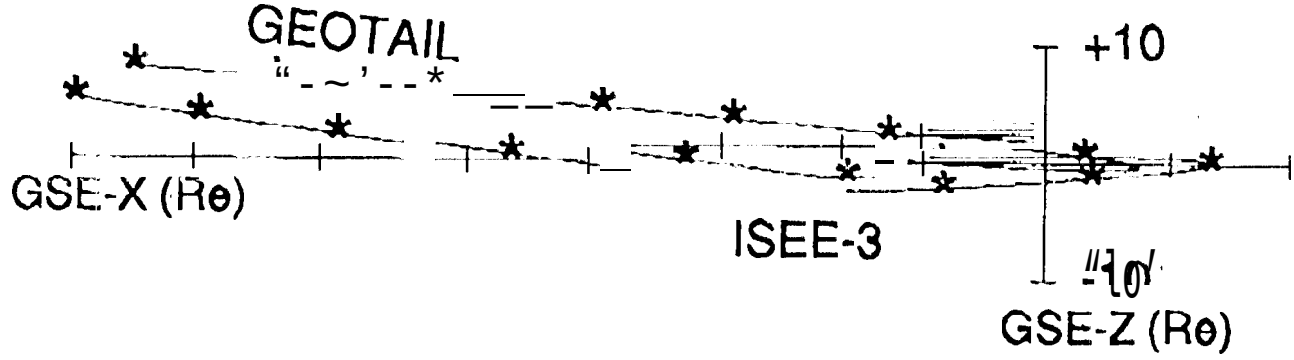
Figure 5. Panels a and b show the normalized amplitudes of the upstream transverse magnetic field fluctuation observed by ISEE-3 (top) and GEOTAIL (middle), respectively. Panel c (bottom) shows the distances D from the nominal bow shock surface to the spacecraft. The curves in panels a and b are the result of the exponential function fitting (see text).

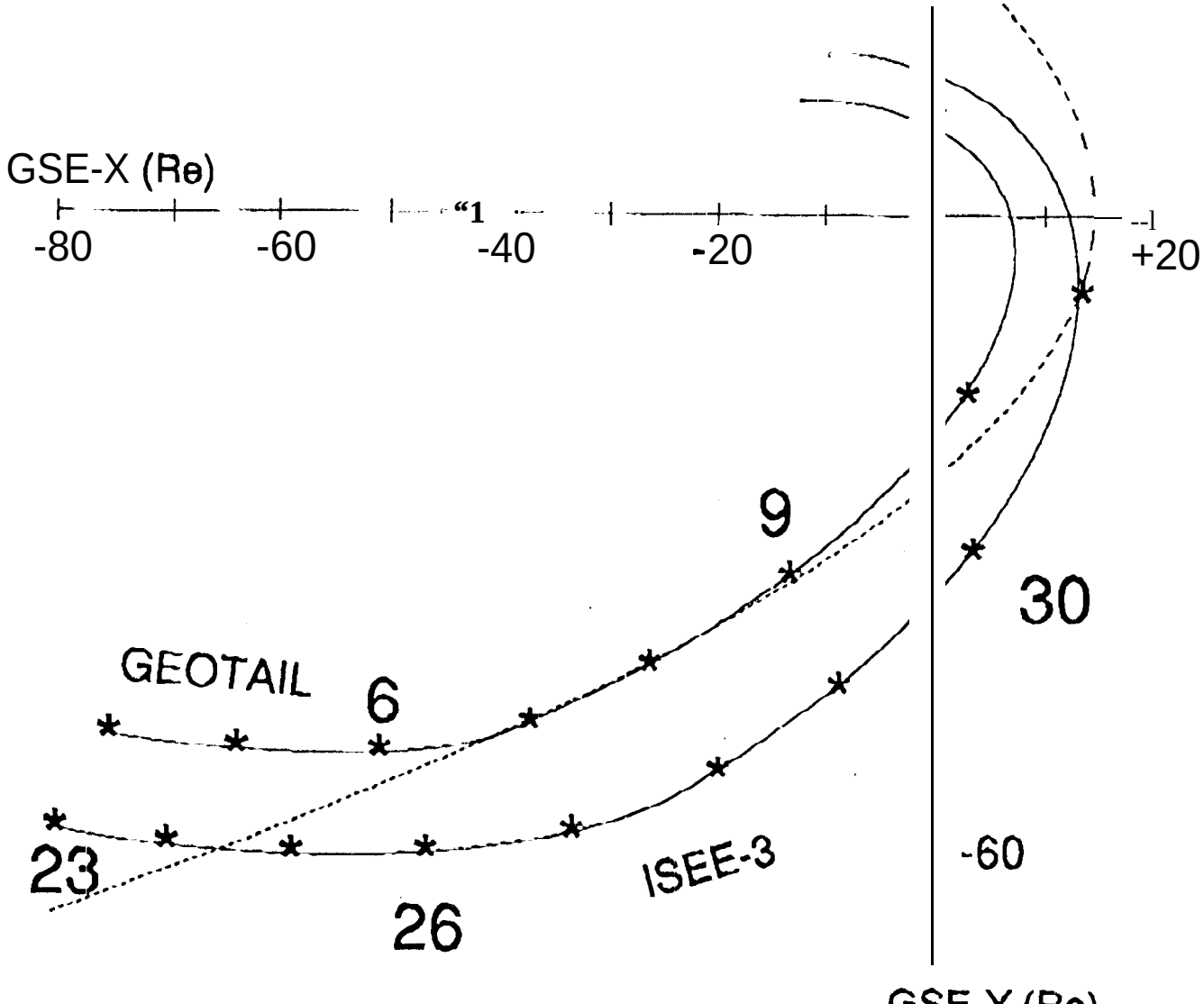
Table 1a. Solar wind parameters for the ISEE-3 upstream interval

date yymmdd	velocity (km/s)	density (1/cm^3)	magnetic field (nT)	M_A
83092?	510.630	2-4	6-7	6-7
830928	480-500	3.6	6-7	6-8
830929	420-460	2-5	b-6	8-9
830930	3s0-390	2-b	5-6	4-7

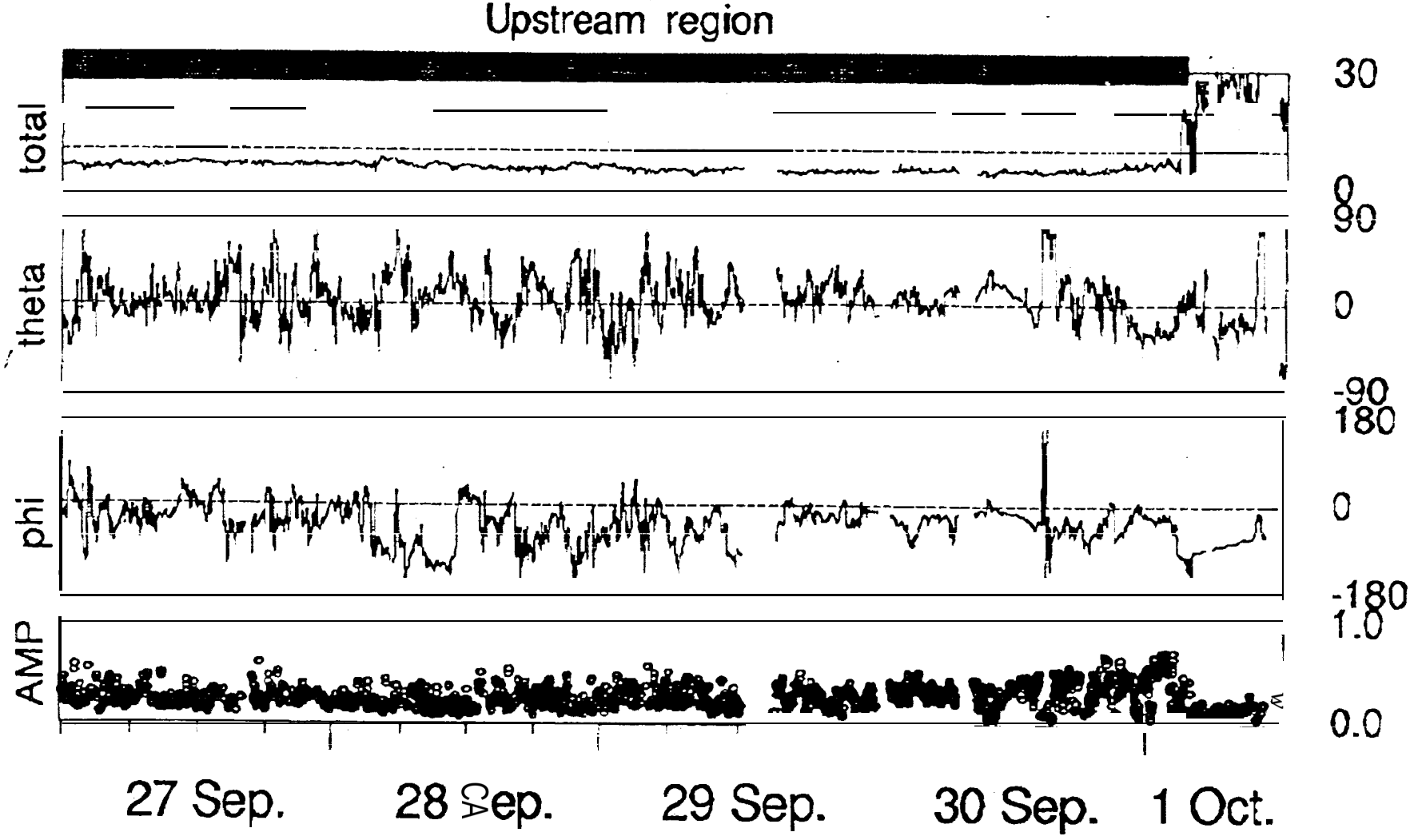
Table 1b. Solar wind parameters for the GEOTAIL upstream interval

date yymmdd	velocity (km/s)	density (1/cm^3)	magnetic field (IIT)	M_A
930806	421-465	8-15	7-8	8.11
9S0807	387-438	7-13	7	'7-11
930808	462-303	3-8	5-7	6-11
990809	468-487	6-9	7	"(-1 u

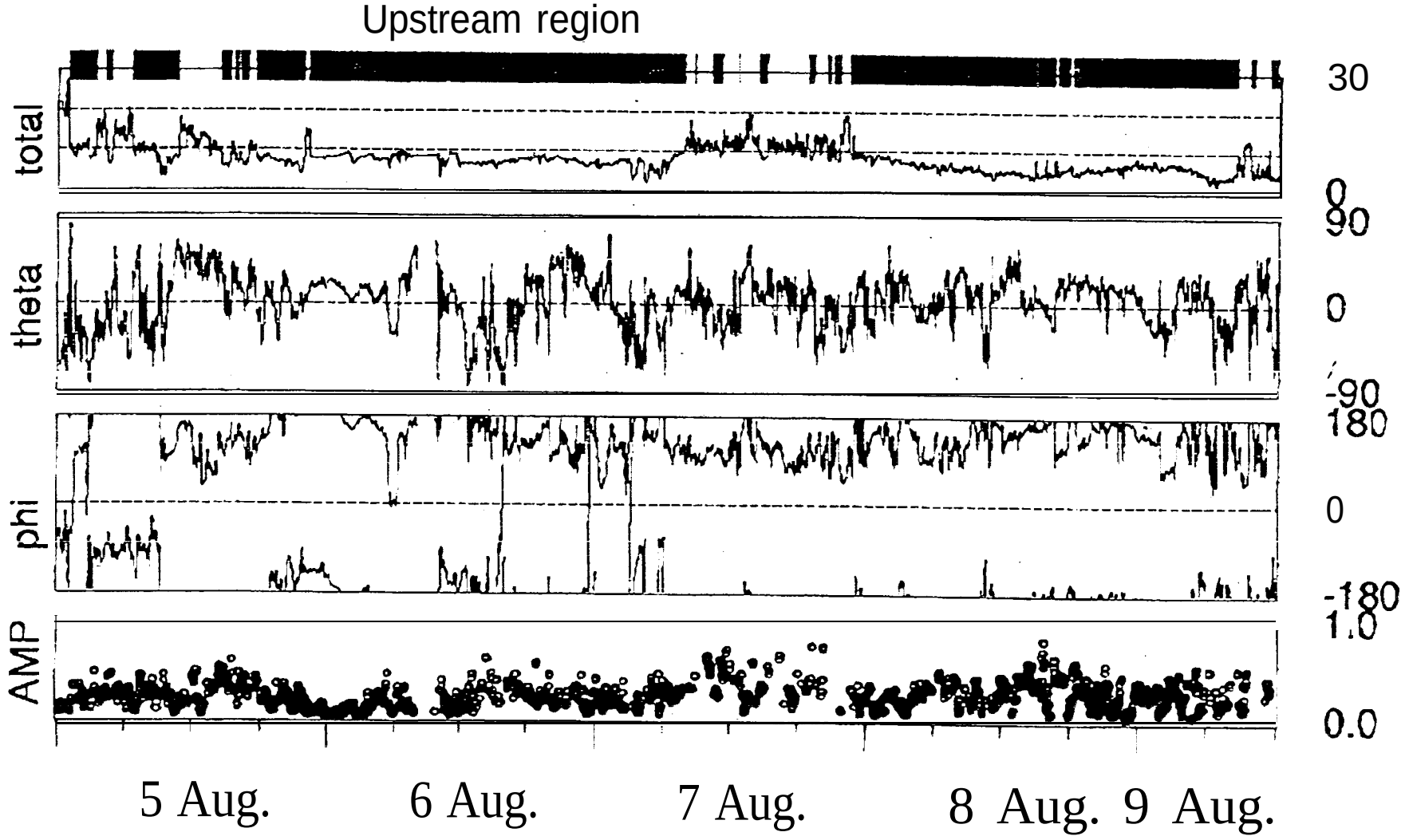

GEOTAIL
+10
GSE-X (Re)
ISEE-3
-10
GSE-Z (Re)


GSE-X (Re)
-80
-60
-40
-20
+20
9
30
GEOTAIL
6
23
ISEE-3
-60
26
GSE-Y (Re)

ISEE - 3 Magnetic Field 1983



GEOTAIL Magnetic Field 1993



Spectrum

6.Aug 1993. 1:39~1 .48

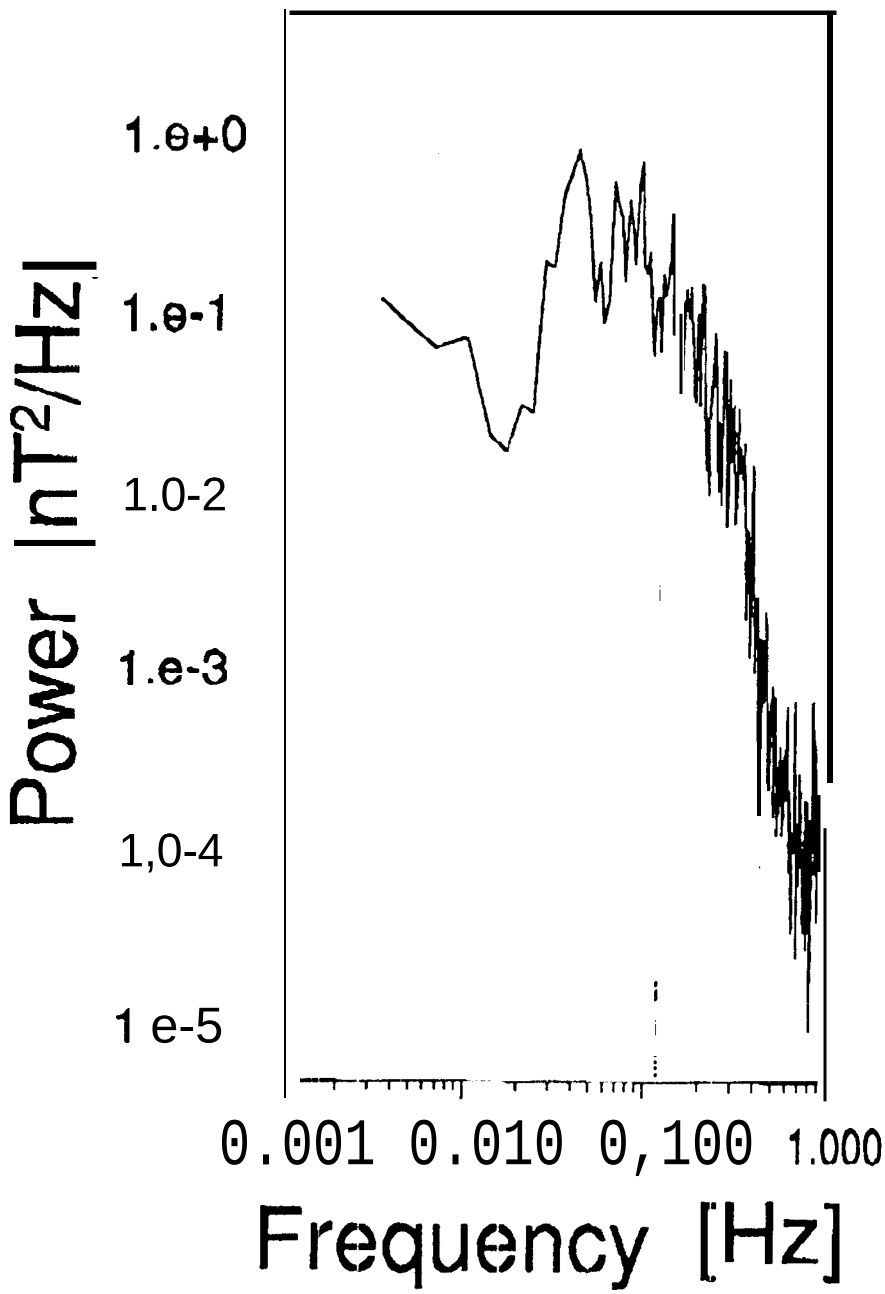
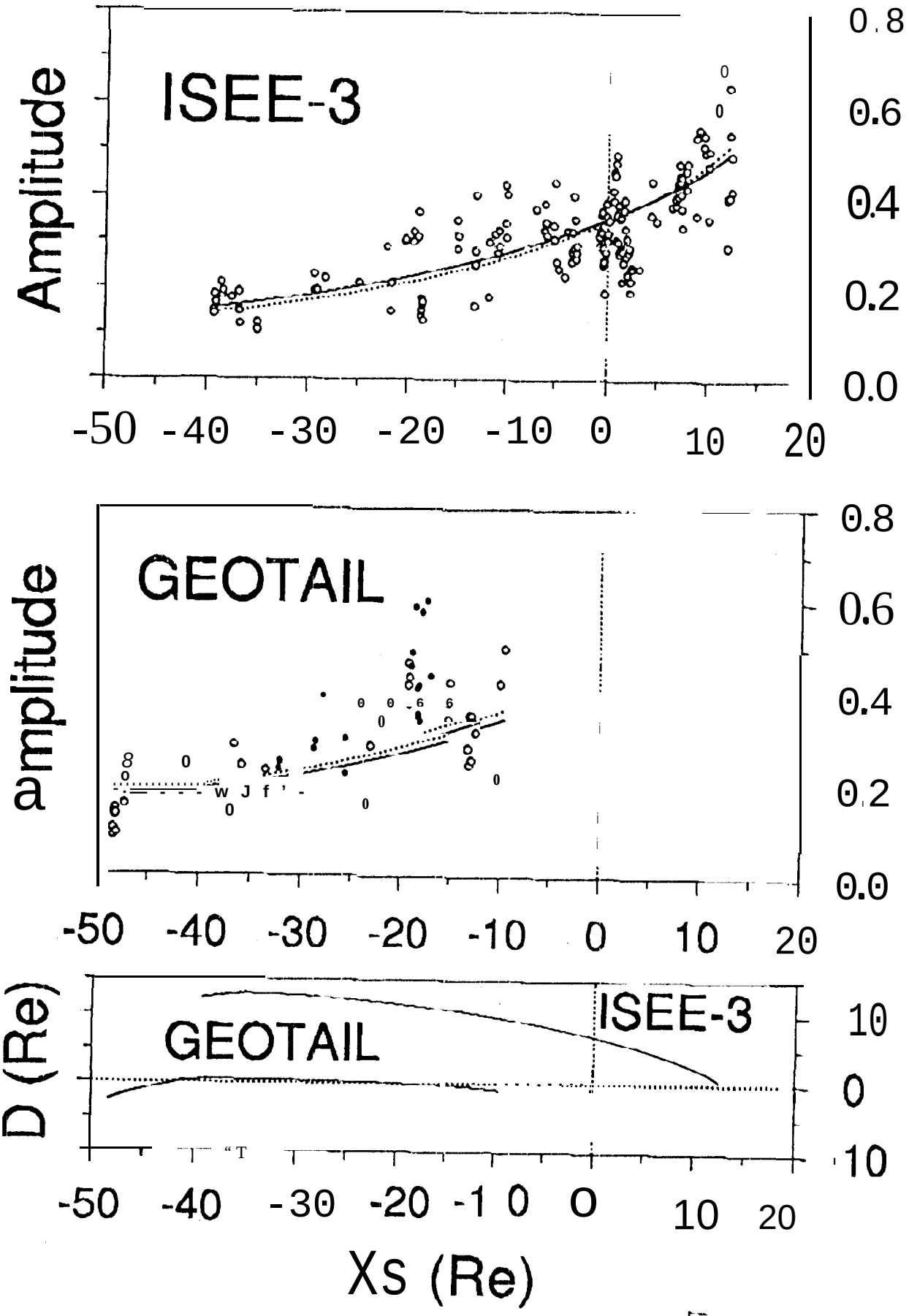


Fig. 4


ISEE-3
Amplitude
0.8
0.6
0.4
0.2
0.0
-50 -40 -30 -20 -10 0 10 20
GEOTAIL
amplitude
0.8
0.6
0.4
0.2
0.0
-50 -40 -30 -20 -10 0 10 20
GEOTAIL
ISEE-3
D (Re)
10
0
-10
-50 -40 -30 -20 -10 0 10 20
Xs (Re)